Mass Reduction of Standing and Flat Crop Residues by Selected Tillage Implements

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Abstract. *Field data were collected to determine the mass reduction of standing residue by selected tillage operations and to develop a set of coefficients that could represent changes in mass between standing, flat, and buried residue pools caused by those tillage operations. Tillage implements used in this study were tandem-disk harrows, chisel plows, and wide-sweep plows. A range of pre-tillage corn and wheat residue conditions were studied, with standing and flat residue pools sampled separately before and after each tillage operation.*

The data show that 7% of standing corn residue was flattened with a wide-sweep plow, 89 to 100% with tandem-disk harrows, 29% with a straight-shank chisel plow, and 76% with a twisted-point chisel plow. Wheat residue data indicated that 53 to 55% of the standing residue was flattened with the wide-sweep plows, 86% for a wide-sweep plow outfitted with a rolling harrow treader attachment, and 86 to 95% for the tandem-disk harrows. The two straight-shanked chisel plows, one outfitted with a drag harrow attachment using coil-spring wire teeth and one without an attachment, flattened 90% and 22% of the standing wheat residue, respectively.

A set of transfer equations also was developed to represent changes in mass between standing, flat, and buried residue pools from tillage operations. Only three coefficients (flattening, burial, and surfacing) are necessary to describe the transfer of mass from one residue pool to another. Coefficient values, determined via a constrained optimization procedure, are presented for each tillage implement on both corn and wheat residues. ***Keywords.** Residue, Crop, Tillage, Burial, Flattening, Incorporation.*

Preserving crop residue on the soil surface is a proven and effective method of controlling erosion caused by water or wind. Residue that is lying prone on the soil surface (flat residue) helps reduce water erosion by lessening the impact of raindrops on the surface and retarding the rate at which water can leave the field through increased infiltration of surface water. Residue left upright (standing residue) is less effective at reducing water erosion than flat residue. However, standing residue is generally more effective in controlling wind erosion than the equivalent mass of flat residue alone, in some cases by an order of magnitude (Hagen, 1993). Standing residue reduces the velocity shear stress near the soil surface and intercepts saltation and creep material transported by the wind. Flat residue reduces the soil surface area exposed to the wind and, therefore, can reduce the emission rate of soil particles from the surface. Also, unanchored flat residue by itself can be susceptible to removal by wind, potentially nullifying any mitigating effects it can have on wind erosion.

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Knowledge of the amount of residue on the surface, both standing and flat, can be used to determine susceptibility to erosion at any time. If reductions in both standing and flat residue by tillage operations are known, then predictive erosion models that consider management practices can determine the potential erosion hazard for a given crop rotation practice. Various erosion models in use today—the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1960); the Wind Erosion Equation (WEQ) (Woodruff and Siddoway, 1965); and the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1991, 1994) take into account management practices. Other models under development by the USDA-Agricultural Research Service, such as the Wind Erosion Prediction System (WEPS) (Hagen, 1991) and the Water Erosion Prediction Program (WEPP) (Laflen et al., 1991), are even more sensitive to the effects of different residue management practices on erosion control.

Most tillage residue studies in the last decade related to erosion control have dealt primarily with flat residue cover in relation to water erosion and have not adequately considered the standing residue component. This study was prompted by the lack of significant data in the literature regarding tillage effects on standing residue and the necessity of including knowledge of the standing residue component in the WEPS model to accurately determine soil susceptibility to wind erosion.

The objectives of this work were to:

- Determine the mass reduction of standing residue by selected tillage operations.
- Develop a set of coefficients that could represent corresponding changes in mass between standing,

flat, and buried residue pools caused by tillage operations.

Three types of tillage implements, tandem-disk harrows, chisel plows, and wide-sweep plows, were used in corn and wheat residue field experiments.

Literature Review

Studies by Woodruff et al. (1965) showed that after-harvest standing residue amount (mass) and height affected the quantity of total surface residue remaining following selected tillage operations. However, they did not attempt to quantify the amount of standing residue remaining after these tillage operations.

Many researchers (Shelton et al., 1993; McCool et al., 1989; Burr et al., 1986; Brown et al., 1992; Todd et al., 1988) have examined the effects of tillage, fertilizer application, winter weathering, and planting on percent crop residue cover. None of these reports made any distinction between standing and flat residue because of an interest in water erosion rather than wind erosion.

The Soil Conservation Service, in conjunction with the Equipment Manufacturers Institute (1992), compiled and published estimated percent cover values of crop residue that remain after passes by various tillage implements. The values presented were based primarily on results from the numerous studies of tillage effects on residue. When data were missing, incomplete, or inconsistent, the values were agreed upon by those involved with the compilation of this list.

Many methods are accepted for estimating the amount of crop residue on the soil surface (Morrison et al., 1993). The most common methods involve estimating percent cover from flat residue. Because of the time and labor involved, as well as residue mass generally being considered irrelevant with respect to water erosion control, most recent tillage residue studies have not made direct mass measurements of residue in the field. However, mass versus percent cover relationships were developed by Gregory (1982). McCool et al. (1990) also presented mass-to-percent cover values for small grains grown in the Pacific Northwest.

Experimental Procedure

Several separate experiments at three sites were performed to investigate the quantity of standing, flat, and buried residues after certain tillage operations. The first experimental set was performed in the summer of 1991, one week after a 2350 kg/ha yield wheat harvest. The next experimental data set was collected in the fall of 1991, two weeks after a corn harvest where the yield was not recorded. These two experiments were performed at the Kansas State University Agronomy Farm near Manhattan, on a Smolan silt loam soil (fine, montmorillonitic, mesic pachic argiustolls). A second location was near Andale, Kansas, on a Bethany silt loam soil (fine, mixed, thermic pachic paleustolls) and involved two separate sets of data collection for wheat residue in the summer of 1992, four and seven weeks after a 2800 kg/ha yield harvest. The final experimental set involved only corn residue, with data being obtained 10 days after a 11 225 kg/ha yield harvest from a site near Wamego, Kansas, on a Muir silt loam soil (fine-silty, mixed, mesic cumulic haplustolls) in the fall of 1992. Table 1 lists the type of tillage implement used and the residue involved for each of the three sites. Estimated tillage speed was 9.2 km/h, and tillage depths were those typically used by the cooperating operators (approximately 10 to 15 cm for wide-sweep plows; 15 to 20 cm for chisel plows; and 10 to 15 cm for tandem disk harrows). Soil moisture contents at time of tillage were not recorded.

Table 1. Tillage implements

Implement	Description	Crop	Year	Location
Disk#1	Tandem Disk Harrow, 5.5 m width 20 cm blade spacing, 56 cm diameter	Wheat Corn	1991	Manhattan
Disk#2	Tandem Disk Harrow, 5.3 m width 23 cm blade spacing, 56 cm diameter	Wheat	1992	Andale
Disk#3	Tandem Disk Harrow, 4.3 m width 23 cm spacing, 46 cm diameter	Corn	1992	Wamego
Sweep#1	Wide-sweep Plow, 1.8 m width one 1.8 m sweep blade	Wheat Corn	1991	Manhattan
Sweep#2a	Wide-sweep Plow, 4.6 m width two 1.5 m and one 1.8 m sweep blades	Wheat	1992	Andale
Sweep#2b	Wide-sweep Plow, 4.6 m width two 1.5 m and one 1.8 m sweep blades single rotary harrow treader attachment	Wheat	1992	Andale
Chisel#1	Chisel Plow, 3.7 m width 30 cm shank spacing, straight pts.	Wheat Corn	1991	Manhattan
Chisel#2	Chisel Plow, 4.6 m width 30 cm shank spacing, straight pts. two rank coil-spring wire teeth harrow attachment with 4.7 cm teeth spacing	Wheat	1992	Andale
Chisel#3	Chisel Plow, 4.6 m width 9 shank, 20 cm shank spacing, twisted pts.	Corn	1992	Wamego

In all experimental sets, standing residue was defined as residue that was attached (anchored) to the soil and not contacting the surface at another point. Flat residue was defined as all other residue including that not anchored to the soil (prone or upright). No distinctions were made between stem and leaf residue. For each experimental site, flat residue was collected and bagged, and then the standing residue was clipped at the soil surface and bagged separately. After all residue was collected and bagged, it was transported to the USDA Wind Erosion Laboratory in Manhattan, Kansas, where it was washed and oven dried at 70° C to a constant weight following the procedure as described by Whitfield et al. (1962).

Pre- and post-tillage samplings were done by removing and bagging the standing and flat residue from within nearly adjacent, inline, sampling cells (fig. 1). If more than one tillage pass was performed, the second cell sampled in a series would represent not only the post-tillage condition of the first tillage pass, but the pre-tillage values for the second tillage pass. Thus, the third cell sampled in a series

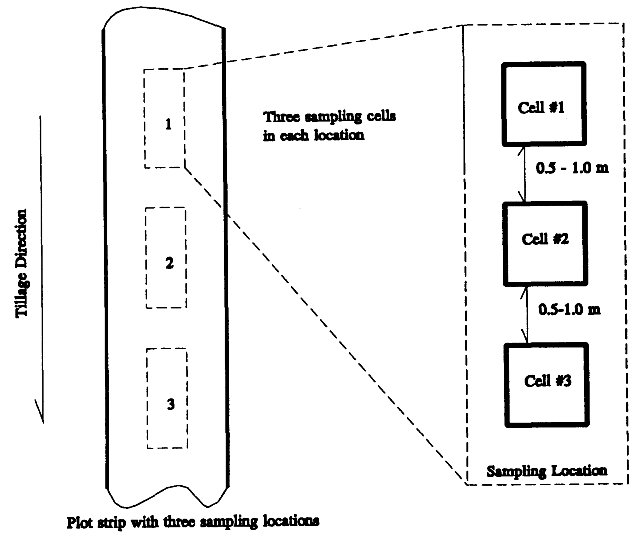

Figure 1–Layout of residue sampling cells.

would become the post-tillage values for the second tillage pass and the pre-tillage values for the third tillage pass, etc.

Limited percent cover data were taken at the Andale and Wamego sites using the line-transect method. Within a particular plot, a two-person team recorded four separate line-transect measurements. All measurements were averaged within a plot, and these numbers were averaged over the total treatment for both before- and after-tillage conditions. In the case of corn residue, pre-tillage conditions were determined by taking 20 measurements at randomly selected locations throughout the test plots. The pre-tillage conditions for each of the two wheat residue level plots were determined by taking four measurements at randomly selected locations in the plots.

Table 2. Corn residue treatments

Site Location	Pretreatment*	Tillage Treatment	Plot Reps	Samples per Plot	Treatment Code
Manhattan	IC	Sweep#1	1	4	M_S
	1 pass Sweep#1	Sweep#1	1	4	M SS
	2 passes Sweep#1	Sweep#1	1	4	M_SSS
	3 passes Sweep#1	Sweep#1	1	4	M_SSSS
	IC	Chisel#1	1	4	M_C
	1 pass Chisel#1	Chisel#1	1	4	M_CC
	IC	Disk#1	1	4	M_D
	1 pass Disk#1	Disk#1	1	4	M_DD
	2 passes Disk#1	Disk#1	1	4	M_DDD
	3 passes Disk#1	Disk#1	1	4	M_DDDD
Wamego	IC	Chisel#3	2	4	W_C
	1 pass Chisel#3	Chisel#3	2	4	W_CC
	1 pass Disk#3	Chisel#3	3	4	W_DC
	2 passes Disk#3	Chisel#3	3	4	W_DDC
	IC	Disk#3	3	4	W_D
	1 pass Disk#3	Disk#3	3	4	W_DD
	1 pass Chisel#3	Disk#3	3	4	W_CD

* Pretreatment is the residue state prior to the tillage treatment represented by the specified tillage passes on the after-harvest residue (IC) at the time of treatment.

Table 3. Wheat residue treatments

Site Location	Pretreatment*	Tillage Treatment	Plot Reps	Samples per Plot	Treatment Code
Manhattan	IC	Sweep#1	1	4	M_S
	1 pass Sweep#1	Sweep#1	1	4	M_SS
	2 passes Sweep#1	Sweep#1	1	4	M_SSS
	3 passes Sweep#1	Sweep#1	1	4	M_SSSS
	IC	Chisel#1	1	4	M_C
	1 pass Chisel#1	Chisel#1	1	4	M_CC
	IC	Disk#1	1	4	M_D
	1 pass Disk#1	Disk#1	1	4	M_DD
	2 passes Disk#1	Disk#1	1	4	M_DDD
	3 passes Disk#1	Disk#1	1	4	M_DDDD
Andale 1	IC	Sweep#2a	3	4	A1_S
	IC	Disk#2	3	4	A1_D
Andale 2	IC (low residue)	Sweep#2b	2	2	A21_S
	IC (high residue)	Sweep#2b	2	2	A2h_S
	IC (low residue)	Chisel#2	2	2	A21_C
	IC (high residue)	Chisel#2	2	2	A2h_D
	IC (low residue)	Disk#2	2	2	A21_D
	IC (high residue)	Disk#2	2	2	A2h_C

* Pretreatment is the residue state prior to the tillage treatment represented by the specified tillage passes on the after-harvest residue (IC) at the time of treatment.

Three primary tillage tool types (wide-sweep plow, chisel plow, and tandem-disk harrow) were studied. However, not every tillage implement was available at each site (table 1). The experimental sites varied in size and shape. Also, sample cell size and number of replications were adjusted across sites based on the investigators' previous experience. For these reasons, the experimental design of each site is addressed individually. Tables 2 and 3 summarize all treatments for both corn and wheat residue experiments.

Manhattan Site

Corn and wheat residue were tilled consecutively up to four times with the same implement (tables 2 and 3). Tillage implements used were a tandem-disk harrow, a chisel plow, and a wide-sweep plow (table 1). Three 60 × 2 m plots, one for each tillage implement, were partitioned and contained four separate sampling locations. Each sampling location was comprised of nearly adjacent, inline cells (0.915 × 0.915 m for wheat and 0.915 × 1.83 m for corn). The adjacent cell locations were selected randomly within the plot between the harvester tire tracks.

Andale Site

Tillage experimentation on wheat residue was performed on two separate dates (late July and mid-August), each with different types of treatments (Andale 1 and Andale 2, table 3). Single tillage passes were performed on the initial postharvest residue remaining at the time of the field experiments on 50 × 10 m adjacent plots. The treatments were replicated in a completely randomized design. Pre- and post-tillage measurements were taken from individual, inline, nearly adjacent, sampling cells measuring 0.915 × 0.915 m.

Andale 1 experimentation consisted of two treatments (replicated three times) using a wide-sweep plow (rotary harrow treader attachment removed) and a tandem-disk harrow. The four adjacent cell locations were selected randomly within the plot area between the harvest tire tracks.

Andale 2 experimentation consisted of six treatments (replicated twice) using a wide-sweep plow (rotary harrow treader attachment included), a tandem-disk harrow, and a straight-point chisel plow with a drag harrow attachment with coil-spring wire teeth. Because a large variation of flat residue was noticed previously at this site, two distinct sampling regions were specified this time for each tillage operation: 1) between the harvest tire tracks, where significant amounts of loose, flat residue was left by the harvesting operation (high residue condition); and 2) outside the tire tracks, where minimal flat residue was present (low residue condition). Line-transect measurements also were taken on these plots.

Wamego Site

Tillage experimentation on corn residue was performed at this site with two implements—a tandem-disk harrow and a twisted-point chisel plow (table 2). Seven separate treatments were performed on the plots: 1) disking after-harvest residue; 2) chiseling after-harvest residue; 3) two diskings of after-harvest residue; 4) two chiselings of after-harvest residue; 5) disking following chiseling of after-harvest residue; 6) chiseling after disking of after-harvest residue; and 7) chiseling after twice disking after-harvest residue.

Treatments were replicated three times in a completely randomized design on individual plots that measured 45 × 8 m. Each plot contained four locations for pre- and post-tillage residue sampling, measuring 1.52 × 2.59 m.

Theory

To represent changes in the mass among each of the three residue pools (standing, flat, and buried) from experimental data, three residue mass-transfer processes were defined: 1) flattening – transfer of standing residue to flat residue; 2) burying – transfer of flat residue and flattened standing residue to buried residue; and 3) surfacing – transfer of buried residue to flat residue on the surface.

The following assumptions were made:

- Conservation of mass applied (total residue before tillage equals total residue after tillage).
- The flattening and burying transfer processes occur sequentially, i.e., the portion of initial standing residue that is flattened was considered part of the flat residue pool acted upon by the burying process.
- No residue from the flat or buried residue pools could enter the standing residue pool.
- The flattening, burial, and surfacing coefficients were assumed to be functions of tillage implement and residue type only.

For the three mass-transfer processes, the following equations were developed:

$$M_{sf} = (1 - C_f) * M_{si} \qquad (1)$$

$$M_{ff} = (M_{si} * C_f + M_{fi}) * (1 - C_b) + M_{bi} * C_s \qquad (2)$$

$$M_{bf} = (M_{si} * C_f + M_{fi}) * C_b + M_{bi} * (1 - C_b) \qquad (3)$$

where

M_{si}, M_{sf} = initial and final mass of standing residue (kg)

M_{fi}, M_{ff} = initial and final mass of flat residue (kg)

M_{bi}, M_{bf} = initial and final mass of buried residue (kg)

C_f = fractional reduction of initial standing residue (decimal)

C_b = fraction of initial flat residue and flattened standing residue that is buried (decimal)

C_s = fraction of initial buried residue brought to the surface (decimal)

These equations reflect the transfer of residue from one residue pool to another by a particular tillage operation. Equation 1 describes the amount (mass) of residue that remains standing after tillage, equation 2 represents the quantity of residue that becomes flat on the surface after tillage, and equation 3 describes the amount of residue below the surface after tillage.

Determination of Transfer Coefficients (C_f, C_b, C_s)

From the experimental data, mass concentrations of standing and flat residues before and after tillage are known (tables 4 and 5). Lacking any other source, the initial buried residue mass within the top 12 cm for after-harvest treatments was estimated from functional relationships used in the RUSLE crop database (Renard et al., 1993). Root mass values of 610 kg/ha and 1017 kg/ha were used for corn and wheat residue, respectively. These values were determined from the pooled averages of the above-ground, post-harvest residue data for corn and wheat obtained from all sites. Post-tillage buried residue mass then was determined using the conservation of mass principle. No adjustments were attempted to account for buried residue below 12 cm, and all buried residue was assumed to be accessible by each tillage implement regardless of tillage depth. Some discrepancies may arise from these simplifications. However, it was felt that, as long as the experimental data collected contained a sufficiently wide range of initial residue conditions, the errors introduced by these assumptions would be insignificant compared to the error in the root mass estimates.

Equations 2 and 3 are not independent. Therefore, a method was needed to determine the "best" pair of C_b and C_s values that satisfied the equations. With a sufficiently wide range of initial residue conditions, a constrained optimization procedure could be used to estimate the coefficients for each tillage operation. A form of the downhill simplex method in multidimensions (Press et al., 1986) was employed to minimize a cost function (eq. 4) with the constraints ($0 \le C_f \le 1$), ($0 \le C_b \le 1$), and ($0 \le C_s \le 1$) to determine the "best" group of coefficient values for a set of data.

$$\text{Error} = \frac{\sqrt{\sum_{1}^{n} \left[F_{ff} - \left((F_{si} * C_f + F_{fi}) * (1 - C_b) + F_{bi} * C_s \right)\right]^2}}{n} \qquad (4)$$

Table 4. Corn residue field data

	Total Mass* (kg/ha)		Residue before Treatment: Mass (kg/ha)				Residue before Treatment: % Total Mass		Residue after Treatment: Mass (kg/ha)				Residue after Treatment: % Total Mass	
			Standing		Flat				Standing		Flat			
Treatment†	Avg.	S.D.	Avg.	S.D.	Avg.	S.D.	Standing	Flat	Avg.	S.D.	Avg.	S.D.	Standing	Flat
M_S	4905	1210	1485	620	2810	822	30	57	635	594	1102	467	13	23
M_SS	4905	1210	635	594	1102	467	13	23	1095	401	1401	624	22	29
M_SSS	4905	1210	1095	401	1401	624	22	29	809	554	1701	994	17	35
M_SSSS	4905	1210	809	554	1701	994	17	35	557	372	1270	532	11	26
M_C	4830	1202	1378	376	2842	923	29	59	972	414	2926	865	20	61
M_CC	4830	1202	972	414	2926	865	20	61	1098	579	2181	1049	23	45
M_D	4488	533	1264	414	2615	2267	28	58	0	0	1664	204	0	37
M_DD	4488	533	0	0	1664	204	0	37	0	0	1409	760	0	31
M_DDD	4488	533	0	0	14tl9	760	0	31	0	0	655	77	0	15
M_DDDD	4488	533	0	0	655	77	0	15	0	0	273	66	0	6
W_C	8824	526	3709	434	4509	783	42	51	906	385	1117	648	10	13
W_CC	8824	S26	906	385	1117	648	10	13	420	344	1240	589	5	14
W_DC	6140	594	441	261	116S	574	7	19	334	281	998	S75	5	16
W_DDC	6419	309	253	160	779	278	4	12	59	S3	474	275	1	7
W_D	6562	1293	2489	1003	3468	490	38	53	284	127	1744	S60	4	27
W_DD	594S	267	227	137	1184	332	4	20	31	43	464	26S	2	8
W_CD	8884	657	984	566	982	504	11	11	168	114	537	135	2	6

* The total mass is the sum of the standing, flat, and buried residue. The buried residue is estimated from RUSLE values for after-harvest conditions and is based on conservation of mass for all other conditions.

† Treatment codes correspond to descriptions in table 2.

Table 5. Wheat residue field data

	Total Mass* (kg/ha)		Residue before Treatment: Mass (kg/ha)				Residue before Treatment: % Total Mass		Residue after Treatment: Mass (kg/ha)				Residue after Treatment: % Total Mass	
			Standing		Flat				Standing		Flat			
Treatment†	Avg.	S.D.	Avg.	S.D.	Avg.	S.D.	Standing	Flat	Avg.	S.D.	Avg.	S.D.	Standing	Flat
M_S	8347	988	4104	931	3227	99l	49	39	1927	1039	2S6	93	23	3
M_SS	8347	988	1927	1039	2S6	9l	23	3	1147	753	611	399	14	7
M_SSS	8347	988	1147	753	611	395	14	7	77	29	1113	596	1	13
M_SSSS	8347	988	77	29	1113	596	1	13	125	215	1257	1276	1	15
M_C	7357	1626	3579	1955	2762	608	49	38	2781	1106	599	425	38	8
M_CC	7357	1626	2781	1106	599	425	38	8	1665	487	2550	1455	23	35
M_D	9987	630	5007	233	3964	521	50	40	694	172	1039	148	7	10
M_DD	9987	630	694	172	1039	148	7	10	192	186	92S	245	2	9
M_DDD	9987	630	192	186	925	245	2	9	46	54	639	195	0	6
M_DDDD	9987	630	46	54	639	195	0	6	14	16	618	634	0	6
A1_S	7737	473	1299	118	5420	388	17	70	581	181	2275	402	8	29
A1_D	7737	473	1299	118	5420	388	17	70	149	85	797	441	2	10
A21_S	2831	177	1595	180	219	1l	56	8	273	196	793	675	10	27
A2h_S	6443	844	1516	331	3909	11l	24	60	157	144	2625	686	3	42
A21_C	2596	107	1375	93	203	101	53	8	126	103	706	214	5	27
A2h_C	5671	1223	12S9	291	3394	140	23	58	149	78	1679	413	3	30
A21_D	2662	332	1292	136	353	206	49	13	53	43	330	102	2	12
A2h_D	5932	1169	1317	403	3598	1490	23	S5	81	37	780	352	1	13

* The total mass is the sum of the standing, flat, and buried residue. The buried residue is estimated from RUSLE values for after-harvest conditions and is based on conservation of mass for all other conditions.

† Treatment codes correspond to descriptions in table 3.

where

F_{si} = initial mass fraction of total residue that is standing
F_{fi} = initial mass fraction of total residue that is flat
F_{ff} = final mass fraction of total residue that is flat
F_{bi} = initial mass fraction of total residue that is buried
n = number of experimental observations

Results and Discussion

Flattening and Burying Coefficients

Based on corn residue data listed in table 4, the disk harrows eliminated the most standing residue as shown by their high flattening coefficients of 0.89 to 1.0 (table 6). The chisel plow with the twisted points, chisel#3, had the next highest flattening coefficient of 0.76. It flattened a significantly greater amount of standing corn residue than chisel#1 (C_f = 0.29), which had straight points and a wider tool spacing. Sweep#1 had a flattening coefficient of 0.57.

The amount of corn residue buried varied among the implements at the Manhattan site, with chisel#1 leaving the most residue on the surface (flat and standing) as shown in table 4. Disk#1 and sweep#1 left approximately the same amount of residue on the surface after tilling initial after-harvest residue. However, sweep#1 actually had a higher burying coefficient (C_b = 0.77) than disk#1 (C_b = 0.65), because the sweep plow did not flatten as much standing residue.

On the Wamego site, chisel#3 left less total corn residue on the surface than disk#3 on the initial tillage pass (table 4). This is reflected by the higher burying coefficient (C_b = 0.85) for chisel#3 than disk#3 (C_b = 0.69) in table 6. However, chisel#3 did not bury as much residue as disk#3 in subsequent tillage passes (table 4). This implies that the burying coefficient for chisel#3 is not a constant as assumed, but may be a function of the pre-tillage residue. Sweep#1 data also appears to follow this trend for both C_f and C_b. On the other hand, disk#1 and disk#3 did not exhibit this trend. Data are insufficient here to fully evaluate possible relationships between C_f, C_b, or C_s and pre-tillage residue/soil parameters.

Table 5 (wheat residue) shows that the disk harrows eliminated the most standing residue, the flattening coefficients were 0.86 to 0.95 (table 7). Sweep#1 and sweep#2a had similar flattening coefficients (0.53 and 0.55), but sweep#2b flattened much more standing residue (C_f = 0.86) because of its rotary harrow treader attachment. This attachment decreased the standing residue remaining after tillage by about 30% more and had a computed individual flattening coefficient of 0.69. Chisel#1 had the lowest flattening coefficient (C_f = 0.22), whereas chisel#2 had a relatively high flattening coefficient (C_f = 0.90) because of the harrow attachment with coil-spring wire teeth harrow attachment.

On the Manhattan site, disk#1 left less total wheat residue on the surface than sweep#1 on the initial tillage pass (table 5). However, the burying coefficient determined for sweep#1 (C_b = 0.97) was greater than the value obtained for disk#1 (C_b = 0.88) as shown in table 7. This is due to sweep#1 leaving more residue standing, 28% of total residue, than disk#1, which only left 7% of the total residue standing on the initial tillage pass (table 5). Again, like the corn residue data for sweep#1, wheat residue data obtained for sweep#1 after previous tillage passes (table 5) suggest that the burying coefficient is probably not a constant for this implement. Chisel#1 left the most wheat residue on the surface.

The Andale experiment data show that the disk-harrow treatments buried the most residue (C_b = 0.86 to 0.88). Sweep#2a, which did not have the rotary harrow treader attachment, had a burial coefficient of 0.79. Sweep#2b had a burial coefficient of only 0.49. Because the rotary harrow treader attachment flattened much standing residue after the sweep plow blades had tilled the soil, the assumption that all flattened residue occurred before burying was violated. If sweep#2b was treated as two separate implements, wide-blade sweep and rotary harrow treader, each with its own C_f, C_b, and C_s, its flattening coefficient would have been higher.

Surfacing coefficient values determined for each of the implements from the simplex solution varied widely (tables 6 and 7). Because of this variability, no attempt is made to draw conclusions based on the C_s values obtained. Two possible reasons for the lack of uniformity in the surfacing coefficient values are that 1) no actual below-ground residue measurements were taken in any treatment and estimates of after-harvest root mass residue were used; and 2) the surfacing coefficient is a more important factor when a significant portion of residue lies below the surface at the time of tillage, which was not the case in all treatment runs for some of the implements used.

Percent Residue Cover

Flat residue on the surface generally is reported in the literature on a percent cover basis. Gregory (1982) derived a relationship between residue cover and residue mass with coefficients for several common crops.

Table 6. Flattening (C_f), burying (C_b), and surfacing (C_s) coefficients for corn residue

Implement	C_f	C_b	C_s
Disk#1	1.00	0.65	0.07
Disk#3	0.89	0.69	0.05
Sweep#l	0.57	0.77	0.37
Chisel#l	0.29	0.45	1.00
Chisel#3	0.76	0.85	0.08

Table 7. Flattening (C_f), burying (C_b), and surfacing (C_s) coefficients for wheat residue

Implement	C_f	C_b	C_s
Disk#l	0.86	0.88	0.07
Disk#2*	0.93	0.88	0.00
Disk#2†	0.95	0.86	O.IO
Sweep#l	0.53	0.97	0.14
Sweep#2*	0.55	0.79	1.00
Sweep#2†	0.86	0.49	0.00
Chisel#1	0.22	1.00	0.60
Chisel#2	0.90	0.68	0.25

* Andale l experiment.
† Andale 2 experiment.

$$FR_c = 1 - \exp(10000 * \lambda * FR_m) * 100 \quad (5)$$

where

FR_c = flat residue cover (%)

FR_m = flat residue mass (kg/ha)

λ = mass-to-cover coefficient (m^2/kg)

Percent cover was estimated for the Wamego experiment using Gregory's value for corn residue ($\lambda = 4\ m^2/kg$) and the flat residue mass data listed in table 4. The data obtained provided reasonable estimates of the actual percent cover as determined by the line-transect measurements (table 8).

Percent cover was estimated from the Andale 2 experiment using Gregory's mass-to-cover coefficient for wheat residue ($\lambda = 5\ m^2/kg$). The percent cover values obtained do not match favorably with measured line-transect values. For the pre-tillage, high residue condition, values obtained using Gregory's conversion coefficient underpredict the measured percent cover by about 16% as shown in table 9. It also severely underestimates the percent cover on the pre-tillage, low residue condition. This was expected, because the low residue pre-tillage condition flat residue was comprised primarily of low density leaf and chaff material. Gregory's mass-to-cover coefficient assumes that the flat residue mass for wheat is composed mostly of higher density stems. However, after-tillage values overpredicted the post-tillage residue cover by about 270%.

The Andale 2 site had above normal rainfall (approx. 133 mm precip.) during the 47 days between harvest and the experiment date. If significant decomposition of the flat wheat residue occurred, this would reduce residue mass on the plots and Gregory's mass-to-cover coefficient (based upon typical after-harvest wheat residue density) would underpredict percent cover. A larger mass-to-cover conversion coefficient ($\lambda = 10\ m^2/kg$) allows Gregory's equation to more accurately predict the actual percent residue cover under the pre-tillage, high-residue condition (table 9). The higher value mass-to-cover coefficient also improves the cover prediction for the low-residue pre-tillage condition, but still underestimates for the same reason Gregory's coefficient does.

However, the new 10 m^2/kg value does not improve the post-tillage percent cover estimates obtained with

Table 8. Percent cover data for flat corn residue

		Pretillage % Cover		Posttillage % Cover		% Cover Reduction Coefficients	
Implement	Treatment*	Est.†	Meas.‡	Est.†	Meas.‡	Meas.§	Literature‖
Chisel#3	W_C	83.5	88.5	36.0	25.1	0.72	0.30-0.50
	W_CC	36.0	25.1	39.1	21.6	0.14	
	W_DC	37.2	34.1	32.9	26.9	0.21	
	W_DDC	26.8	22.5	17.3	18.7	0.17	
Disk#3	W_D	75.0	87.0	50.2	34.2	0.61	0.30-0.60
	W_DD	37.7	35.5	16.9	20.8	0.41	
	W_CD	32.5	30.0	19.3	20.0	0.33	

* Treatment codes correspond to descriptions in table 2.

† Equation 5, $\lambda = 4\ m^2/kg$.

‡ Measured line-transect values.

§ Calculated from line-transect values.

‖ Based on non-fragile residue (SCS and EMI, 1992).

Table 9. Percent cover data for flat wheat residue

		Pretillage % Cover			Posttillage % Cover			% Cover Reduction Coefficients	
Implement	Treatment*	Est.†	Est.‡	Meas.§	Est.†	Est.‖	Meas.§	Meas.#	Lit.**
Sweep#2b	A21_S (low res)	10.4	19.7	74.5	32.7	9.1	11.3	0.85	0.20-0.30
Chisel#2	A21 C (low res)	9.7	18.4	74.5	29.7	8.1	11.5	0.85	0.40-0.60
Disk#2	A21_D (low res)	16.2	29.7	74.5	15.2	3.9	4.7	0.94	0.60-0.75
Sweep#2b	A2h_S (high res)	85.8	98.0	97.5	73.1	27.0	17.0	0.83	0.20-0.30
Chisel#2	A2h_C (high res)	81.7	96.6	97.5	56.8	18.2	12.1	0.88	0.40-0.60
Disk#2	A2h_D (high res)	83.5	97.3	97.5	32.3	8.9	8.9	0.91	0.60-0.75

* Treatment codes correspond to descriptions in table 3.

† Equation 5, $\lambda = 5\ m^2/kg$ (Gregory's suggested value).

‡ Equation 5, $\lambda = 10\ m^2/kg$ (Pretillage "best fit").

§ Measured line-transect values

‖ Equation 5, $\lambda = 1.2\ m^2/kg$ (Posttillage "best fit").

\# Calculated from line-transect values.

** Based on fragile residue (SCS and EMI, 1992).

Gregory's suggested mass-to-cover value. For predicting the after- harvest residue cover from the flat residue mass, 1.2 m^2/kg was found to be the best value. It is not entirely clear why this occurred. Gregory's mass-to-cover value is based on after-harvest residue primarily composed of stems, which would be expected to have the greatest residue density. The field situation definitely did not have surface residue of density greater than after-harvest wheat residue. Thus, there is no explanation as to why the mass-to-cover value that "best fit" the data in the post-tillage condition would be smaller than Gregory's suggested value.

Percent Cover Reduction Coefficients

Effects of individual tillage operations on surface residue generally have been represented in the literature by percent cover retained coefficients for different types of residue. For comparison purposes, the complement, percent cover reduction coefficients (reduction in percent residue cover) will be used.

For the tillage operations on the corn residue, the actual percent cover burial coefficients derived from the line-transect measurements (table 8) tend to lie outside of or near the extremes of the ranges provided by SCS and EMI (1992). The twisted-point chisel plow (chisel#3) buried a much greater proportion of residue on a cover basis (0.72) than suggested by SCS and EMI (0.30 to 0.50) when tilling the after-harvest residue. However, the percent cover reduction coefficients obtained for the chisel#3 operations performed on the pre-tilled conditions (0.14, 0.21, and 0.17) are well below the SCS and EMI range as shown in table 8.

Even though the measured percent cover reduction coefficients were essentially within the range provided by SCS and EMI for tandem-disk harrow operations on corn (0.30 to 0.60), disk#3 values showed a trend similar to that obtained with the chisel#3 operations. Again, a relatively high percent cover burial coefficient (0.61) was obtained for the disk#3 treatment on the after-harvest residue, but low values (0.41 and 0.33) for the pre-tilled conditions.

For all tillage operations on wheat residue, the actual percent cover burial coefficients computed from the line-transect measurements (table 9) were much greater than the upper values suggested by SCS and EMI (1992) for fragile residues. The Andale 2 experiment did not involve any pre-tillage treatment conditions. Therefore, potential differences in percent cover reduction coefficients caused by prior tillage could be evaluated as done on the Wamego corn data.

The lack of agreement between published ranges of percent cover reduction values (SCS and EMI, 1992) and our actual measurements implies that other factors, besides pre-tillage residue cover, can strongly influence the resulting post-tillage residue cover left on the surface. Also, wide variations in the measured percent cover reduction coefficients for the corn residue suggest that the tillage implements did not bury residue only as a function of cover. This is implied by the fact that SCS and EMI provides ranges for each implement on different types of residue. Thus, care must be used to select the correct percent cover reduction value for an implement based upon the pre-tillage soil/residue condition to accurately predict the after-tillage residue cover.

Summary

Flattening, burying, and surfacing coefficients (on a mass basis) for various tillage operations using tandem-disk harrows, chisel plows, and wide-sweep plows were determined with corn and wheat residues. For corn residue, the data showed that the tandem-disk harrows flattened the greatest amount of residue, followed by a twisted-point chisel plow, wide-blade sweep, and a straight-point chisel plow. Mass burying coefficients ranged from 0.45 to 0.85 for these implements. For wheat residue, the tandem-disk harrows again flattened the greatest amount of standing residue followed by a straight-point chisel plow with a drag harrow attachment with coil-spring wire teeth, a wide-sweep plow with a rotary harrow treader attachment, a wide-sweep plow with no attachments, and a straight-point chisel plow with no attachments. Mass burying coefficients ranged from 0.49 to 1.0 for these implements on wheat residue.

Estimates of residue percent cover using Gregory's suggested corn residue mass-to-cover coefficient (4 m^2/kg) agreed well with line-transect measurements. However, Gregory's value of 5 m^2/kg for wheat residue underpredicted the measured pre-tillage residue cover by 16% and overpredicted the measured post-tillage residue cover by 270%.

The percent cover reduction coefficients derived from measured line-transect data on the corn residue for all implements included a fairly wide range of values, with some of them significantly different than those reported in the literature. The coefficients for the wheat data are more consistent but still well outside the range reported in the literature. Percent cover data from this study indicate that the conversion factor value relating residue mass-to-percent cover is extremely critical in determining the cover actually present on the field surface. Also, the data suggest that published percent cover reduction coefficients may not be accurate when applied to tillage operations on residue subjected to decomposition.

Representing tillage residue burial effects on a percent cover basis raises three concerns: 1) the additional mass of flat residue that was originally standing prior to tillage is not accounted for directly in the coefficient; 2) the relationship of flat residue mass-to-percent cover is not a constant over time because of decomposition processes; and 3) residue burial may not be strictly a function of pre-tillage residue cover.

This study points out that additional research is required in at least three areas in order to further refine relationships for residue cover and mass: 1) determine flattening and burying coefficients for other residue types subject to different tillage implements; 2) determine the effect of decomposition on flattening and burial coefficients; and 3) determine which factors besides pre-tillage residue amount affect residue burial. This research also points out that experimental design and sampling procedure are critical to determining accurate and consistent relationships for these situations.

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